Asymmetric Leptons for Asymmetric Tops

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We propose an efficient method to explore models which which produce like-sign tops at the LHC, using the total charge asymmetry of single lepton events instead of like-sign dileptons. As an example, the method is implemented on a Z' Model, which can explain the top pair forward-backward asymmetry at Tevatron. We show that a large region of the parameter space of this model can be reached using the existing data set at the LHC.

INTRODUCTION

Clarifying the nature of electroweak symmetry breaking (EWSB) is one of the primary missions of the LHC [1]. Whatever the agent of EWSB, it must couple most strongly to the the most massive particles of the Standard Model (SM), and it is imperative to examine the properties of the heavy quarks and gauge bosons in order to confirm the SM predictions for their properties. In particular, the top quark as the most massive particle discovered to date and the only fermion whose mass lies close to the electroweak scale itself, is a natural laboratory to explore these questions. The Tevatron program has successfully discovered top, measured its mass, and verified many of its expected features. As the LHC collects data in earnest, it acts as a top factory and offers unprecedented potential to examine top quark properties and study production at high energy.

In fact, the Tevatron may already be providing hints for new physics in the top sector. The observable of primary interest is the forward-backward asymmetry in top production,

$$A^t_{\rm FB} \equiv \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}, \tag{1}$$

where $\Delta y = y_t - y_{\bar{t}}$ is the difference between the rapidity of the top and that of the anti-top. It characterizes how often the top (as opposed to anti-top) tends to go in the direction of the incoming quark in the reaction $q\bar{q} \to t\bar{t}$ as observed from the $t\bar{t}$ center of mass frame. The measurements [2–5] show an interesting deviation from the expectations of the Standard Model, where it receives negligible leading order contributions from electroweak production $q\bar{q} \to Z^* \to t\bar{t}$, and small (but in principle measurable) contributions of $6 \pm 1\%$ at next-to-leading order in QCD [6]. A recent update to the measurement [5] finds $A^t_{\rm FB} = 15.8 \pm 7.5\%$ and further indicates that the deviation is small for top quarks produced with small invariant mass, but grows large ($48\pm 11\%$ measured compared to the SM prediction of $9\pm 1\%$) for invariant masses $M_{t\bar{t}} \geq 450$ GeV. This feature is exciting because it is consistent with the expected influence of heavy physics operating just beyond the kinematic reach of the Tevatron. Inspired by these results, a plethora of theoretical proposals have appeared [7–11] attempting to explain it in terms of heavy new physics.

If this measurement does indeed represent a glimpse of heavy physics just beyond the reach of Tevatron, there is potential for enormous deviations at the LHC [12–15], whose large center-of-mass energy allows it to rather easily produce states too heavy for the Tevatron. The specific signatures at the LHC can help distinguish between particular models. For example, some models produce resonances in $t\bar{t}$ production, whereas others contain new particles decaying into top and a light quark. Some models produce *like-sign tops* (tt or $\overline{tt}$) [13], and the separate rates of tt and $\overline{tt}$ encode information about the couplings of the new states. In fact, like-sign top pairs are a striking signal of physics beyond the Standard Model, one with very little genuine physics background.

The typical signature of like-sign top production uses semi-leptonic decays to measure the charge of both of the decaying top quarks (along with the b-tagged jets and missing energy such decays produce). It is a striking signal with very little SM background (predominantly from jets faking one of the leptons), but it does come at the cost of requiring both tops to decay into either an electron or muon, a combined branching ratio of $(2/9)^2 \sim 5\%$. With very limited statistics, this may severely limit

the effectiveness of the signature.

A related observable is the *single lepton charge asymmetry*, which also looks at top pair production, comparing the number of top decays producing a positive charged lepton with the number producing a negatively charged lepton,

$$\mathcal{A}_{1\ell} \equiv \frac{N(\text{top pair} \to 1\ell^+) - N(\text{top pair} \to 1\ell^-)}{N(\text{top pair} \to 1\ell^+) + N(\text{top pair} \to 1\ell^-)} \,. \quad (2)$$

Events containing two or more isolated leptons are vetoed[1]. It is aimed at like-sign top production, since $t\bar{t}$ processes necessarily produce no asymmetry. It further specializes to theories where the number of tt pairs is different from the number of $\overline{tt}$ pairs, making use of the fact that the LHC is a pp collider, with more valence quarks than anti-quarks available in the initial state. The primary advantage is that it captures a larger fraction of the like-sign top production, since one top decays hadronically, with a net branching ratio of $2(2/9)(2/3) \sim 30\%$. Thus, with limited statistics it may be able to show a deviation which would not yet be significant in a traditional dilepton-based like-sign top reconstruction. Even with enough statistics for the traditional like-sign top search, it provides a separate handle with different systematics to help pin-down the like-sign top signal. For example, it is less sensitive to the fake background from a jet faking a lepton, assuming that the charge assigned to the mis reconstructed lepton is roughly 50% positive and 50% negative.

In this article, we examine the prospects to use the single lepton charge asymmetry to make an early identification of physics beyond the Standard Model in the form of an anomalous tt production. The technique itself is general, but we apply it in particular to the model of [7], which invokes a Z' with flavor off-diagonal couplings to explain the Tevatron top forward-backward measurement. We find the single lepton charge asymmetry to be a powerful test of such models, and that a significant portion of the parameter space can be reached with modest amounts of data.

[1] Note also that similar charge asymmetries have been suggested in the context of single top production [16].

AN ILLUSTRATIVE MODEL

To illustrate the utility of the single lepton charge asymmetry measurement, we consider a model containing a neutral vector Z' whose interactions are given by,

$$\delta\mathcal{L} = Z'_\mu \bar{u}_R \gamma^\mu \left(g_X t_R + g'_X u_R\right) + \text{c.c.}. \quad (3)$$

It was shown in [7] that this model can generate the observed forward-backward asymmetry for viable choices of the parameters; for example the parameter choices

$$M_{Z'} = 160 \text{ GeV}, \;\; \alpha_X = 0.024, \;\; \alpha'_X \approx 0.002, \quad (4)$$

where $\alpha \equiv g^2/4\pi$, and so on. As shown in [7], α'_X cannot be much larger without running into constraints from dijet searches, and we will ignore it for the purposes of our discussion. This assumption does have some impact when we discuss sources of fake events which would contribute to the $t\bar{t}$ cross section measurement. Ref. [7] further focuses on Z's lighter than the top itself, in order to evade constraints from like-sign top production at the Tevatron.

TOP PAIR PRODUCTION CROSS SECTION

Before examining the single lepton charge asymmetry, we consider the ramifications of the Z' model on the top pair production rate at the LHC. The Z' will contribute to $u\bar{u} \to t\bar{t}$, interfering with the $u\bar{u}$-initiated SM process, and will in addition result in the processes $uu \to tt$ and $\bar{u}\bar{u} \to \overline{tt}$ (the imbalance of which results in the single lepton charge asymmetry). Whether these two latter processes contribute to a given measurement of top pair production depends on the top decay modes under consideration. "Dilepton" top pair events typically require that the leptons be of opposite charge to suppress fake backgrounds, and will not register tt or $\overline{tt}$ events. The "lepton + jets" mode in which one top decays semileptonically and the other hadronically, will measure the sum of $t\bar{t} + tt + \overline{tt}$ production. Thus, the Z' model could reveal itself either through a discrepancy between the top pair production cross section measured in the lepton + jets mode and the SM expectation, or in tension between measurements of the lepton + jets mode and the dilepton mode.

At the current time, ATLAS [17] and CMS [19] (which so far has only released dilepton-based measure-

ments) measurements of the top pair production rate derived from about 2.9 pb^{-1} of integrated luminosity have large enough uncertainties on the individual measurement channels so as to make it difficult to imagine resolving tension between the dilepton and lepton + jets measurements. However, the ATLAS measurement of 142 ± 60 pb [17] in the combined $e + \mu$ single lepton channels nevertheless contains useful information.

In order to estimate the rate of tt production which effectively contributes to the ATLAS measurement, we begin with a sample of ordinary SM $t\bar{t}$, generated at the parton level with Madgraph/Madevent [20], with the CTEQ6L1 parton distribution functions (PDFs) [21] and a renormalization/factorization scale of $m_t = 172.5$ GeV. We apply a K-factor of $K = 1.67$ to match the SM NNLO rate of $164.6^{+11.4}_{-15.7}$ pb [22]. The events are hadronized and showered by Pythia [23]. The detector response is simulated with PGS4 [24] using the default `pgs_card_atlas.dat` card file, using the k_T jet algorithm with cone size $R = 0.4$. We apply the ATLAS $1\mu + \not{E}_T + \geq 4j$ (b-tagged) selection criteria [17] to find the fraction of events accepted by the ATLAS analysis.

Following the same methodology, we generate $t\bar{t}$ and tt events (the rate of $\bar{t}\bar{t}$ is negligible for data sets up to a few fb^{-1}) in the Z' model. We continue to apply $K = 1.67$ for the $t\bar{t}$ rate, but make the more conservative choice of leaving the tt events at their strict tree level estimate. We apply the same reconstruction cuts, determining the actual efficiency for tt events $\varepsilon(tt)$ to pass them, and then unfold with the SM efficiency $\varepsilon(t\bar{t})_{\rm SM}$. The effective unfolded cross section to be compared with the ATLAS measurement is thus,

$$\sigma_{\rm unfolded}(t\bar{t}) = \frac{\sigma(t\bar{t})\varepsilon(t\bar{t}) + \sigma(tt)\varepsilon(tt)}{\varepsilon(t\bar{t})_{\rm SM}} \, . \qquad (5)$$

In Fig. 1, we show the effective (including both like-sign and opposite-sign) top pair cross section which would be measured in the single muon + jets channel, as a function of α_X and for several choices of $M_{Z'}$. Overlaid the predictions of the Z' model is the ATLAS measurement and its one and two sigma uncertainty bands. We see that for small Z' masses, ATLAS is already probing some of the relevant parameter space to explain the $A^t_{\rm FB}$ measurement through its $t\bar{t}$ cross section measurement, but much of the parameter space remains unconstrained.

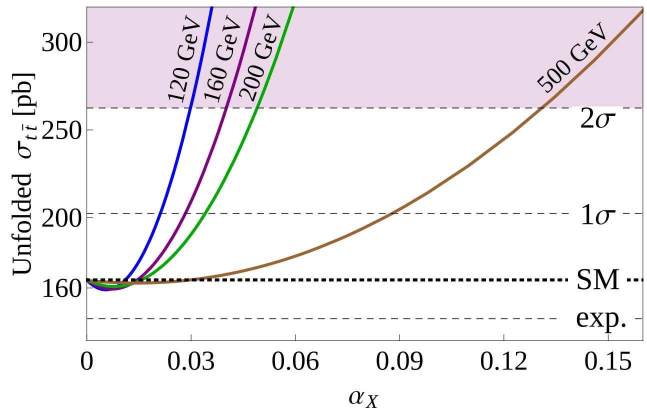

FIG. 1. The effective $t\bar{t}$ cross section which would be reported by ATLAS (7 TeV), as function of α_X, for several values of the Z' mass. The shaded region is 2σ away from the ATLAS single-lepton (e/μ combined) measurement [17].

SINGLE LEPTON CHARGE ASYMMETRY

We now turn to the single-lepton charge asymmetry $\mathcal{A}_{1\ell}$ in the context of the Z' model. We are looking for the excess leptons from top decay in the process $uu \to tt$, driven by the large up quark valence PDFs. there will be an excess of positively charged leptons, resulting in a non-zero value of $\Delta N = N(\ell^+) - N(\ell^-)$ in the $\ell + 4j$ (b-tagged) sample. We will find that measuring this excess is an effective way to probe this model even at the early LHC.

One of the key issues is understanding the non-top pair backgrounds, some of which themselves exhibit a single lepton charge asymmetry. In many cases, these backgrounds can be estimated with the help of the data itself. We focus on the single muon plus at least four jets with at least one jet b-tagged ($\mu + \geq 4j$ (b-tagged)) for our analysis, because it is clean, with the smallest expected "fake" (non-top) background [17]. Apart from being the cleanest, it also avoids contributions from tZ' events (the expected rate of which depends on α'_X). Such contributions do not typically pass the $\ell + \geq 4j$ cuts, though they would be present in the $\ell + 3j$ sample.

The $\mu + \geq 4j$ (b-tagged) channel is defined by the following selection criteria [17]:

- The event contains exactly one muon:
    - ◇ $p_T > 20$ GeV and $|\eta| < 2.5$;
    - ◇ separation $\Delta R > 0.4$ from any jet with $p_T > 20$ GeV;

- ◇ scalar sum of transverse momenta for all tracks within a cone of $\Delta R = 0.4$ is less than 4 GeV;

- $\not{E}_T > 20$ GeV and $\not{E}_T + m_T(W) > 60$ GeV, where $m_T(W) \equiv \sqrt{2p_T(\mu)\not{E}_T\left\{1 - \cos\left[\phi(\mu) - \phi(\not{E}_T)\right]\right\}}$;

- at least four jets with $p_T > 25$ GeV and $|\eta| < 2.5$;

- at least one b-tagged jet.

The background to our signal comes from many processes which produce a single muon along with ≥ 4 jets, passing these cuts. Some of these such as $t\bar{t}$ itself, Z + jets and QCD jet production (where a jet is mis-tagged as a lepton) do not possess an intrinsic lepton charge asymmetry, but for a finite dataset may fluctuate, and thus represent an important uncertainty on a measured value. Others, such as W + jets or single top production [25] contribute directly to the asymmetry, and must be properly accounted for in order to isolate the contribution from top pair production. The full set of backgrounds considered is listed in Table I. For each background process, we determine the "effective cross section", defined as the cross section after imposing the ATLAS μ + $\geq 4j$ (b-tagged) cuts. The ATLAS cross section measurement provides estimates for the rates derived from Monte Carlo and passed through the full ATLAS detector simulation [17]. We list the total effective cross sections for the background processes in the second column of Table I.

The W + jets and single top processes also result in their own non-zero contributions to $\mathcal{A}_{1\ell}$ driven by the fact that at large parton x there are roughly twice as many u as d valence quarks in the proton, resulting in $\mathcal{A}_{1\ell} \sim 1/3$. In practice, both processes also receive contributions from subprocesses initiated by sea quarks and gluons, which are charge-symmetric and lead to $\mathcal{A}_{1\ell} < 1/3$. Since these are subdominant components of the background anyway, we make the conservative choice to set them both to 1/3 in the current study. For example, the charge asymmetry in inclusive $W \to \mu\nu$ events has been measured to range from 0.15 to 0.3 for muon rapidities between 0 and 2.0 [18]. For more precise studies, it would be desirable to determine these contributions more precisely, either from Monte Carlo estimates, or directly from the data (using larger datasets). With precise enough independent determinations, these background biases may be subtracted out to obtain a clean measurement of the excess over the SM. But even if the asymmetries were known precisely, the systematic uncertainties on the effective cross-sections of the background processes must be propagated. The resulting systematic error on the difference between single positive and single negative lepton events (ΔN) is

Background Process	σ_{eff}[pb]	$\mathcal{A}_{1\ell}$
$t\bar{t}$	5.17 ± 1.17	0
W+jets	0.586 ± 0.552	+1/3
Z+jets	0.034 ± 0.034	0
Single top	0.241 ± 0.069	+1/3
QCD jets	0.276 ± 0.173	0
SM combined	6.31 ± 1.31	+0.044

TABLE I. An estimate of the SM background for the single muon charge asymmetry $\mathcal{A}_{1\ell}$. The corresponding effective cross-sections inferred from [17] are also indicated, along with their systematic errors (including the luminosity error), as well as our conservative choices for their intrinsic single lepton charge asymmetry.

$$\delta_{\text{sys}}(\Delta N) = \frac{1}{3}\sqrt{\delta\sigma^2_{\text{eff}}(W+\text{jets}) + \delta\sigma^2_{\text{eff}}(\text{single top})} \times L$$
$$\simeq 0.185\left(\frac{L}{\text{pb}^{-1}}\right), \tag{6}$$

where L is the collected integrated luminosity. In addition, all processes contribute to the statistical error on ΔN,

$$\delta_{\text{stat}}(\Delta N) = \sqrt{N_{SM}} = \sqrt{6.31\left(\frac{L}{\text{pb}^{-1}}\right)}. \tag{7}$$

Note that the small effective cross sections of W+jets and single top events ensure that their systematic effect is small even if our estimate of the corresponding asymmetries is bad. This is of course based on the assumption that the main background process, namely $t\bar{t}$, has little or no asymmetry.

For the Z' model, we simulate the rates of tt production as described above, and select events in the μ+ $\geq 4j$ (b-tagged) channel. This results in the prediction for $\mathcal{A}_{1\ell}$ corresponding to a given choice of $m_{Z'}$ and α_X. The significance of the measurement is,

$$s = \frac{\sigma_{\text{eff}}[tt]\,(\alpha_X, m_{Z'})}{\sqrt{\delta^2_{\text{stat.}}(\Delta N) + \delta^2_{\text{sys.}}(\Delta N)}}. \tag{8}$$

In Fig. 2, we plot the contours of fixed expected significance of the $\mathcal{A}_{1\ell}$ measurement in the $(m_{Z'}, \alpha_X)$ plane,

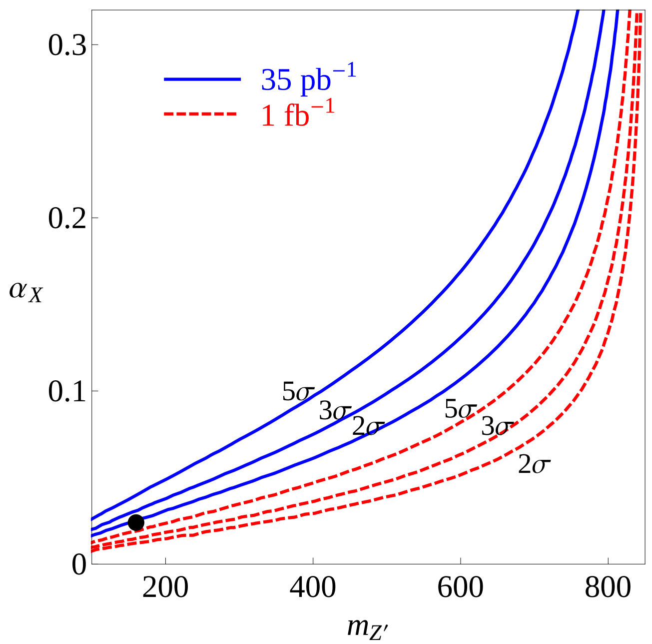

FIG. 2. Significance levels (2σ, 3σ, 5σ) for $L = 35$ pb^{-1} and $L = 1$ fb^{-1} in the $(m_{Z'}, \alpha_X)$ plane, from measurement of the single-lepton charge asymmetry, using the $1\mu + \not{E}_T + \geq 4j$ (b-tagged) channel at 7 TeV. The black dot represents the point ($m_{Z'} = 160$ GeV, $\alpha_X = 0.024$) discussed in the text.

both for the current data corresponding to 35pb^{-1}, as well as for a future measurement with 1 fb^{-1}. Already, the current data allows one to constrain a significant portion of the parameter space consistent with the Tevatron measurement, if the central value of $\mathcal{A}_{1\ell}$ turns out to be zero. With 50 pb^{-1} of data, the parameter choice ($M_{Z'} = 160$ GeV and $\alpha_X = 0.024$) mentioned above can be excluded at better than the 95% CL if the SM expectation is obtained. With 1 fb^{-1} of data, the same point can be discovered at the 5σ level.

CONCLUSIONS

We have discussed a simple method to probe models which produce like sign tops at the LHC, through observation of an imbalance between the number of top pairs leading to a single positively charged lepton and the number of negatively charged single leptons. It has the advantage of requiring less statistics than a traditional like-sign top search relying on two like-sign leptons from the top decays. Even when statistics are sufficient for the like-sign top measurement to be effective, it remains a good complement to such a measurement, because it is sensitive to different backgrounds and different experimental errors.

We have illustrated how it works for a particular Z' model designed to explain the Tevatron measurements of $A^t_{\rm FB}$, and find that it is expected to be able to say something non-trivial even with the current data set of 35 pb^{-1}. With larger data sets it can exclude or discover a significant portion of the relevant parameter space. Nonetheless, it is much more general, and can be applied to any model producing like-sign tops.

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